Magnetic Behavior of Small Patterned Structures – Dots, Bars and Rings

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Outline

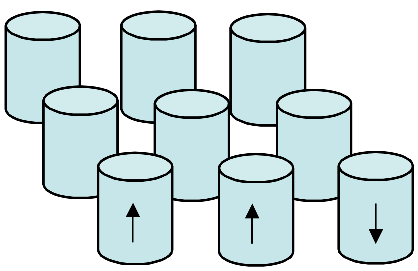
Introduction
Fabrication of Magnetic Nanostructures
Properties of Magnetic Dot Arrays
Properties of Multilayer Bars and Magnetic Rings
Conclusions

Introduction

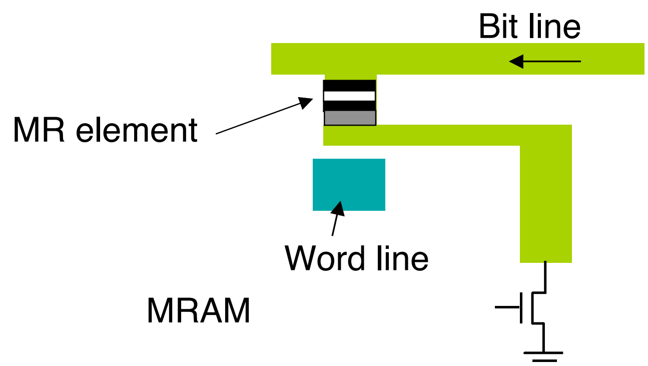
Lithographically-patterned particles have applications in patterned media, magnetic random access memories and other magnetic devices. We are interested in:

developing methods to fabricate arrays of particles with sub-50 nm period for use in **patterned media**,

making ring- and bar-shaped multilayer structures for **MRAM** applications.



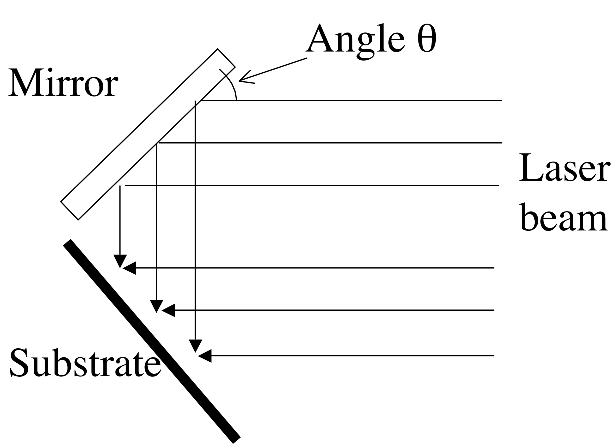
Patterned Media



MRAM

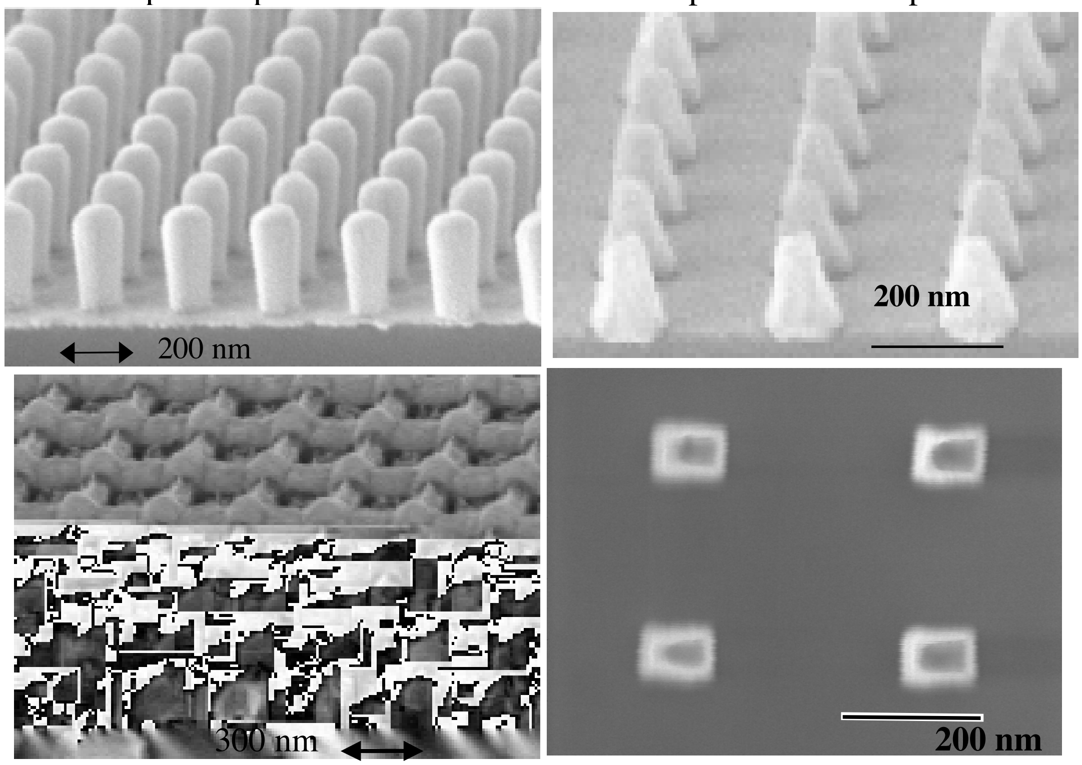
Fabrication of Nanomagnets
Interference Lithography

Two laser beams interfere at a substrate to produce a standing wave that exposes a resist with a grating pattern. A second exposure can be used to make a pattern of holes or dots in the resist. A hole pattern can be used as a template for electrodeposition or evaporation and liftoff processing. A dot pattern can be used as an etch mask for patterning a sputtered magnetic film.



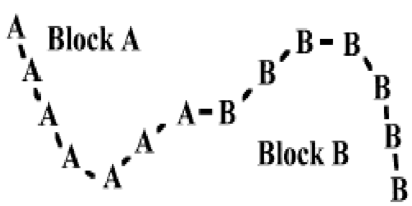
Examples of structures made by interference lithography

Electrodeposited pillars   Evaporated conical particles

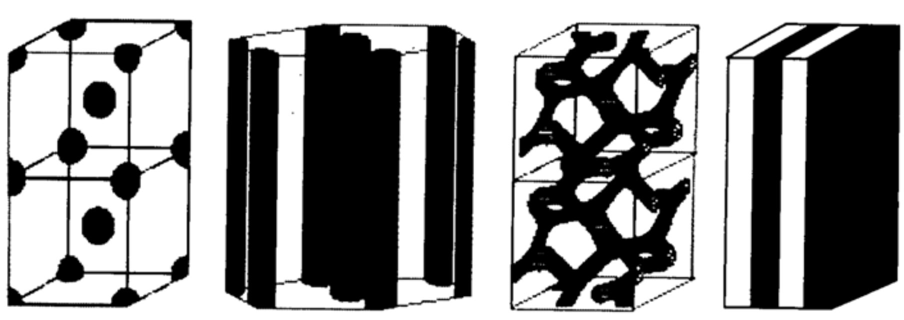


Etched lines   Etched multilayer rectangles

Block copolymers



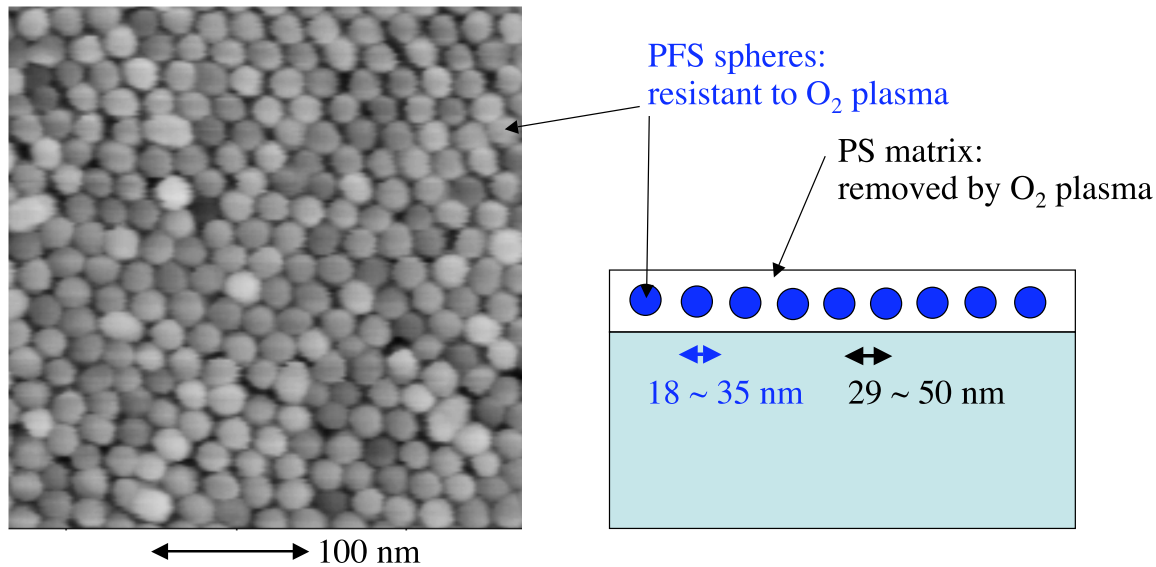
Block copolymers consist of two immiscible blocks, A and B. Depending on the volume fraction of each component, a range of morphologies can be obtained on annealing, with periodicities of a few nm and higher. These self-assembling systems are promising as nanolithography templates.



Spheres   Cylinders   Gyroids   Lamellae

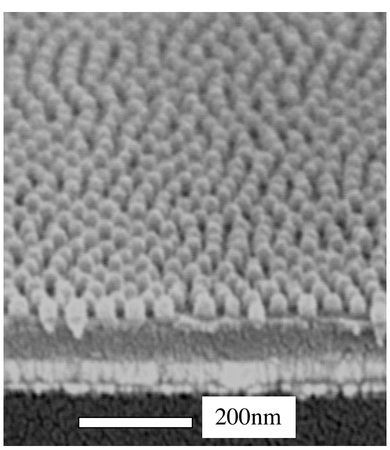
Bates F.S. & Fredrickson G. H. Annu. Rev. Phys. Chem. **41**, 525 (1990)

Block Copolymer Lithography

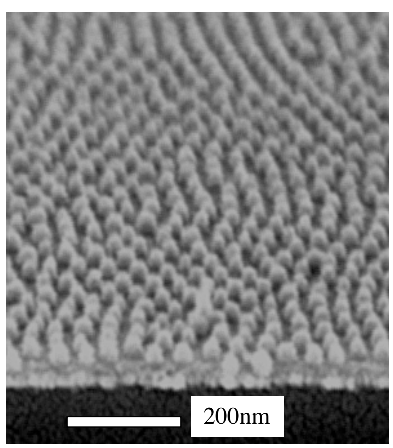


A monolayer of spheres of a spherical-morphology block copolymer self-assembled on a surface can be used as a lithography template. Polyferrocenyldimethylsilane (PFS) - Polystyrene (PS) provides good etch selectivity (~20:1 in oxygen).

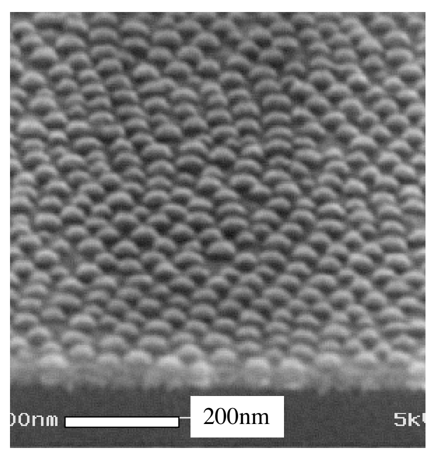
Pattern transfer from Template to Co layer



Pattern in polymer



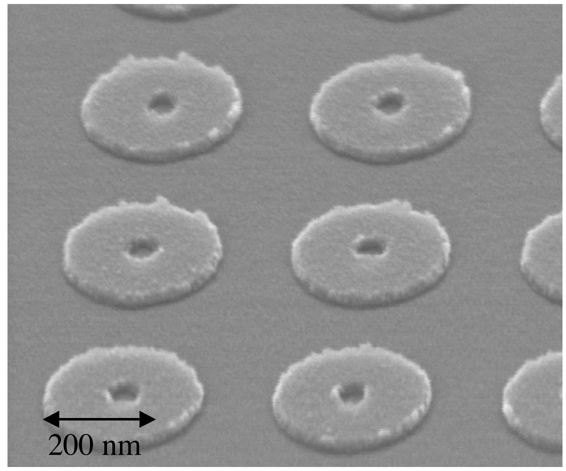
Pattern in W



Pattern in Co

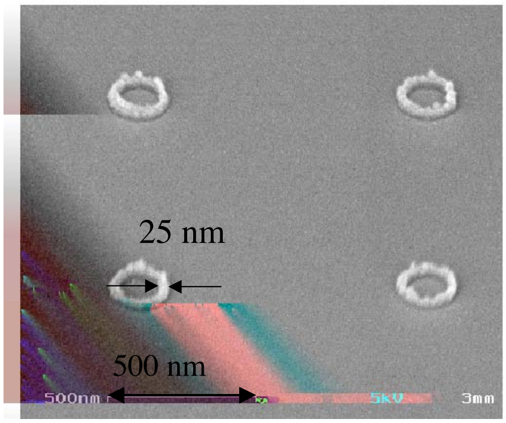
Ion-beam etching process is optimized by using Ne^+ ion-beam to increase selectivity between W and Co.
35nm-diameter magnetic ‘dots’ with 56 nm spacing were made.

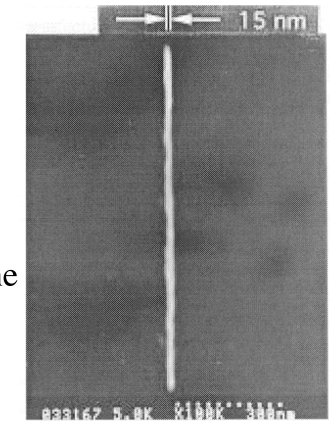
Electron beam lithography



Examples of rings and lines made by e-beam lithography using PMMA resist and liftoff processing

F.J. Castaño

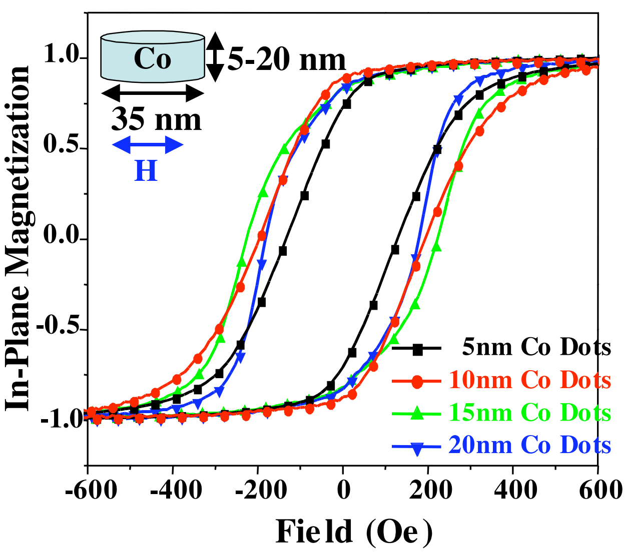




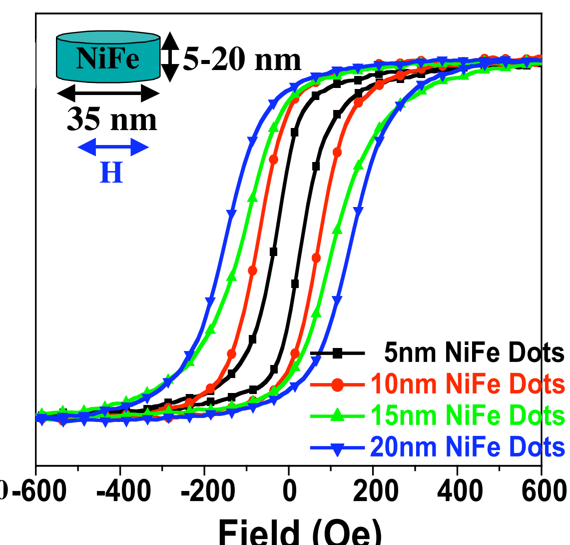
15 nm wide line from Chou, Proc. IEEE 85 652 (1997)

Hysteresis Loops of Magnetic Dot Arrays

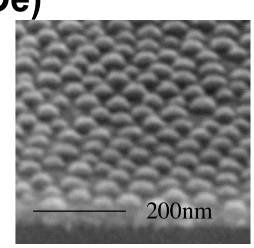
Co



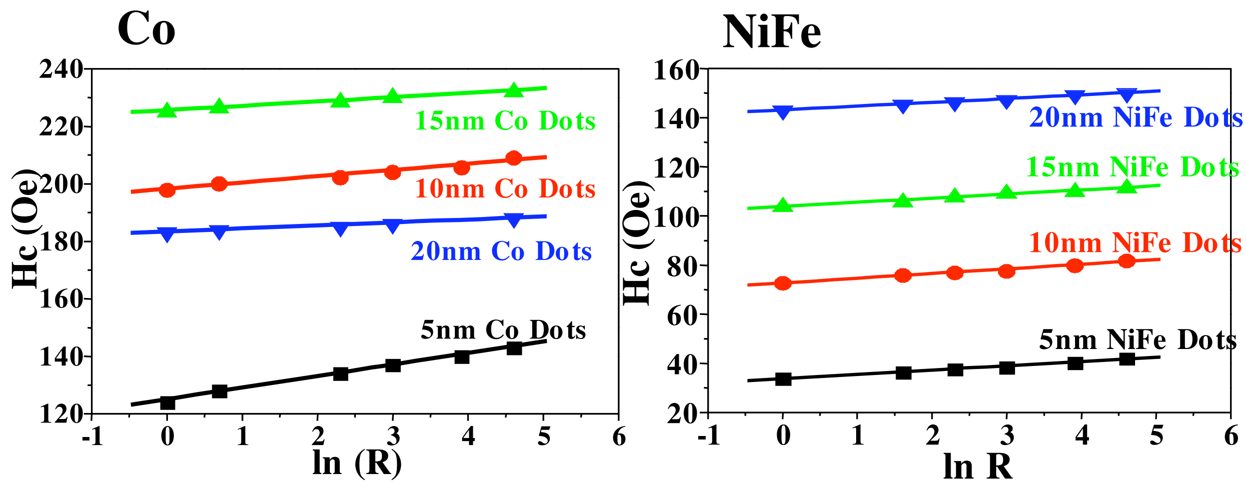
NiFe



Arrays are magnetized in plane. In-plane coercivity increases with dot thickness, and is higher for Co. Switching field distribution is a result of variability interactions between dots



Time-dependent coercivity measurements



Data are fitted to $H_c(R) = \text{const} + (k_B T/M_s V^*) \ln(R)$

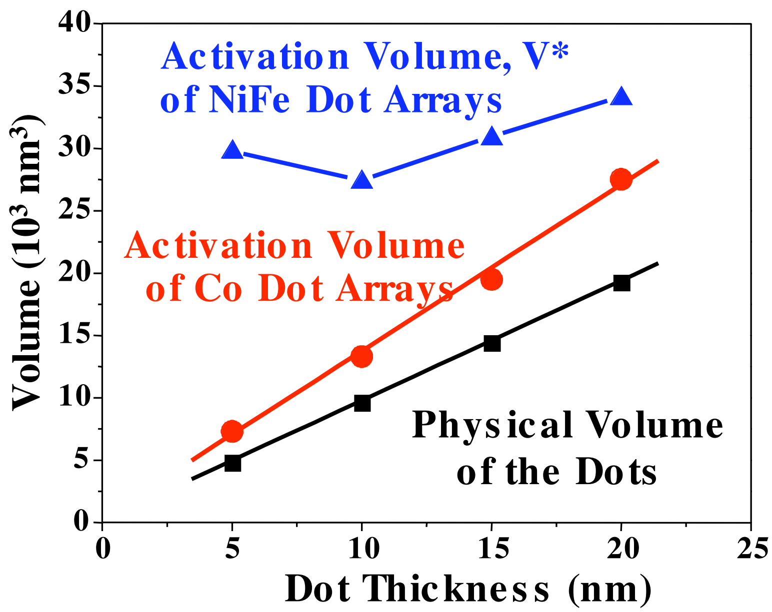
R = field scan rate

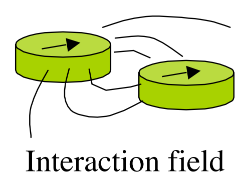
V* = activation volume (switching volume)

The slope gives V*; the intercept gives the energy barrier.

The dots are small enough to show thermally-assisted reversal.

Switching Volume in Magnetic Dot Arrays



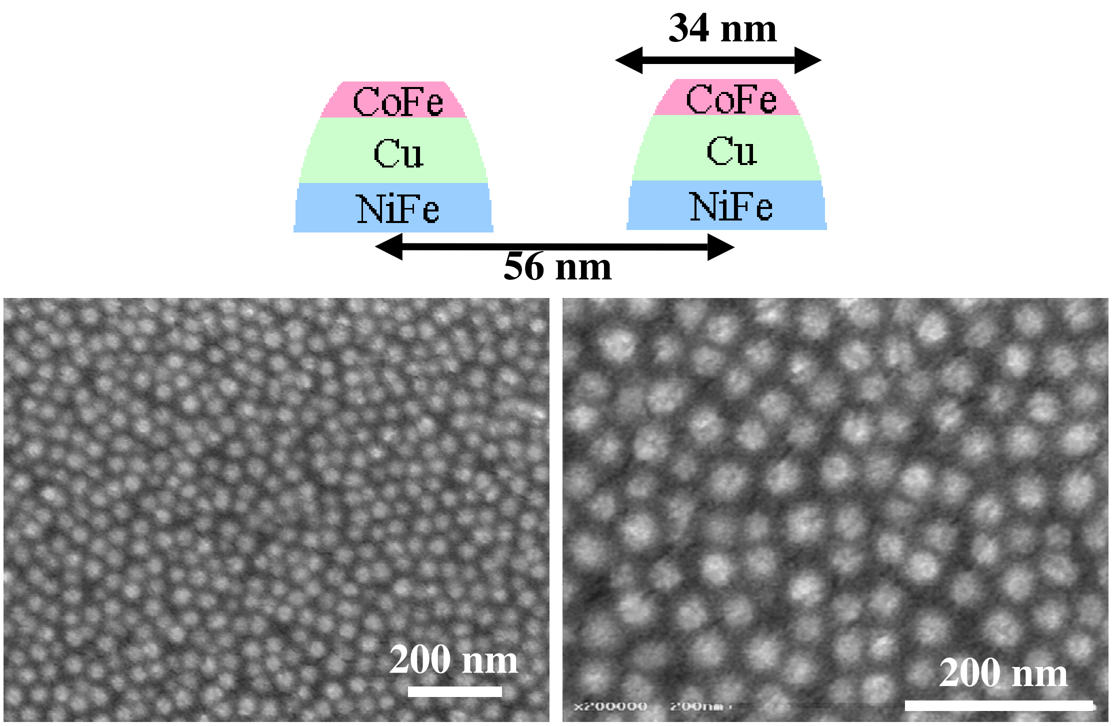


Magnetostatic interactions ⇒ Dots switch cooperatively.

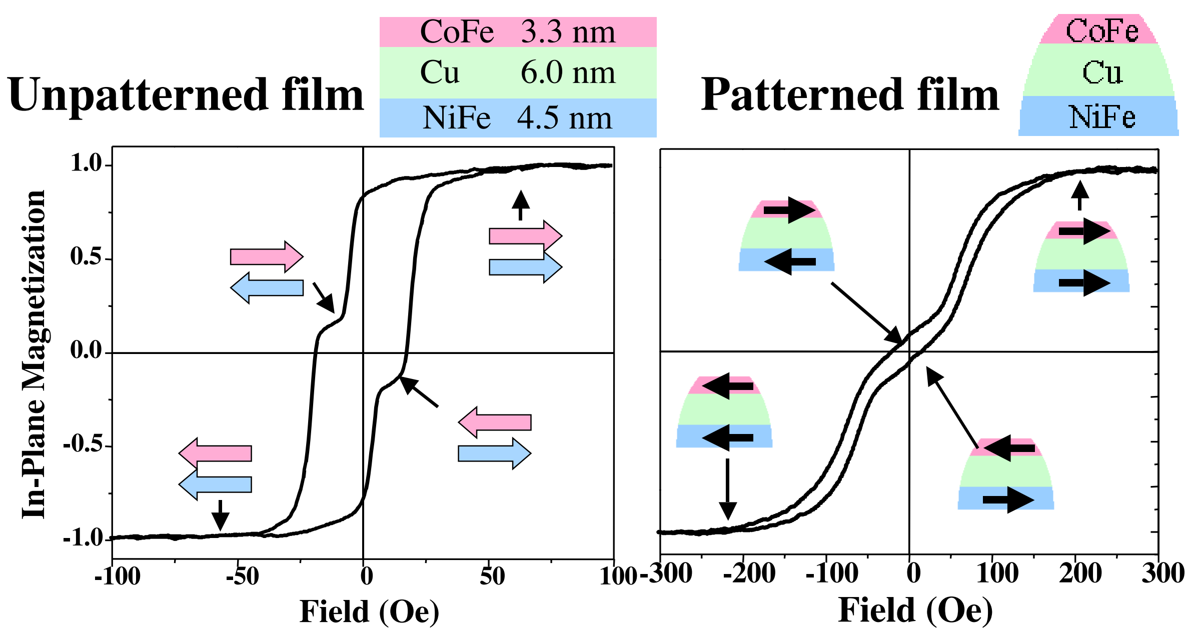
The in-plane magnetization and the strong interactions within these particular arrays dominate the behavior.

CoFe/Cu/NiFe Dot Arrays

(CoFe 3.3 nm / Cu 6.0 nm / NiFe 4.5 nm)



CoFe/Cu/NiFe Dot Arrays



There is still separate switching of the two layers, even on this size scale.

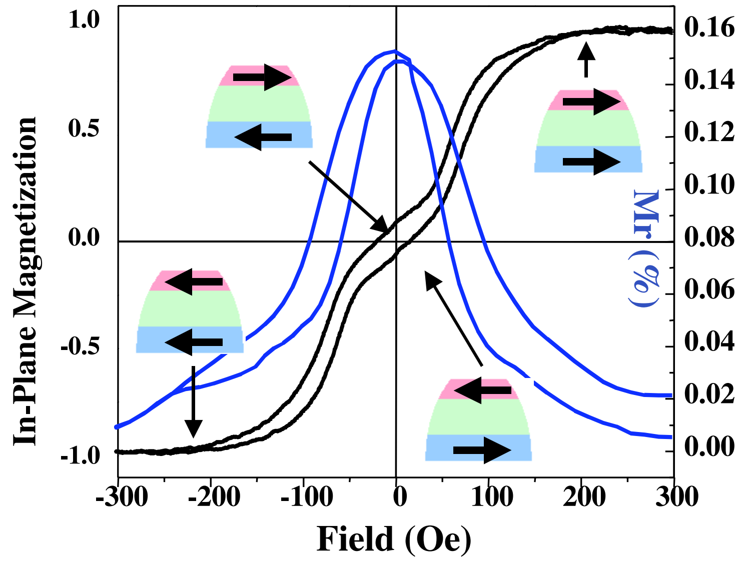
Negative Hc of NiFe layer ⇒ strong magnetostatic interaction between NiFe and CoFe layers.

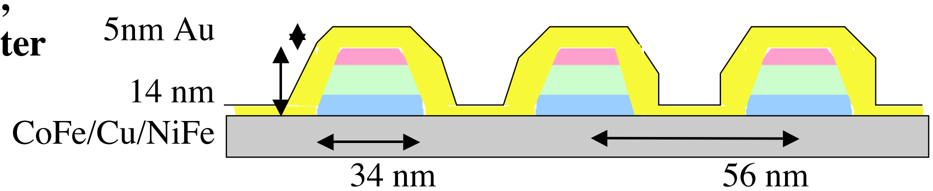
CoFe/Cu/NiFe Dot Arrays: Magnetoresistance

The GMR of dots was 0.15%, compared to 0.7% for the unpatterned film.

Caused by shunting of the Au, plus disruption of the edges of the multilayer.

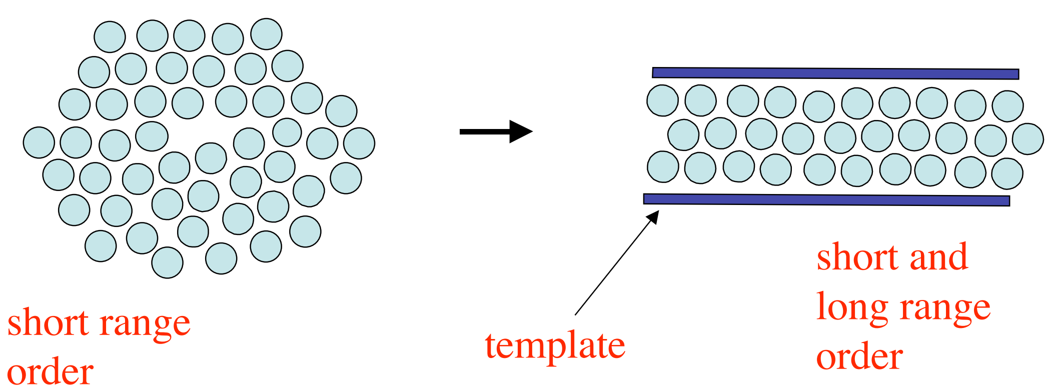
Multilayer elements still show GMR, even at a diameter of 34 nm.





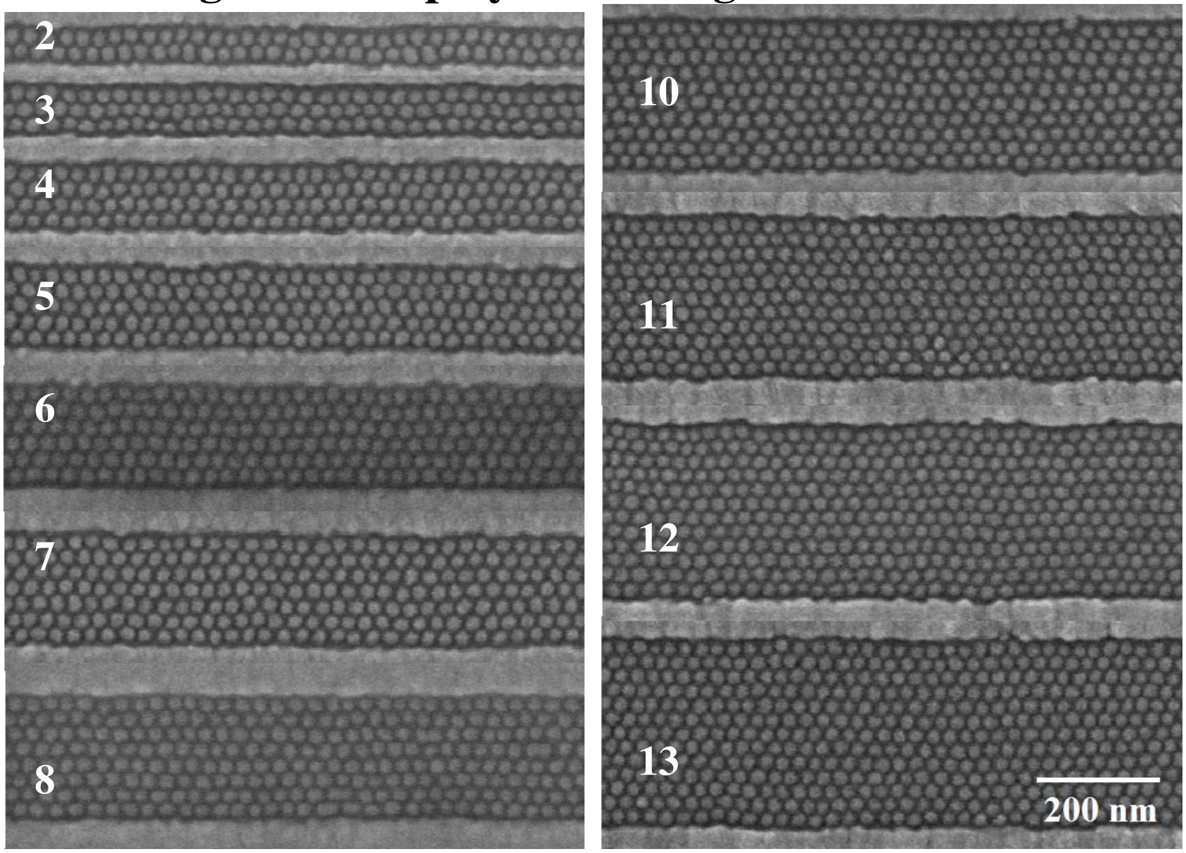
Improving Ordering of Block Copolymer Lithography using Patterned Substrates

A template is formed using, for example, an e-beam lithography process. This enforces long-range order into the self-assembling system.

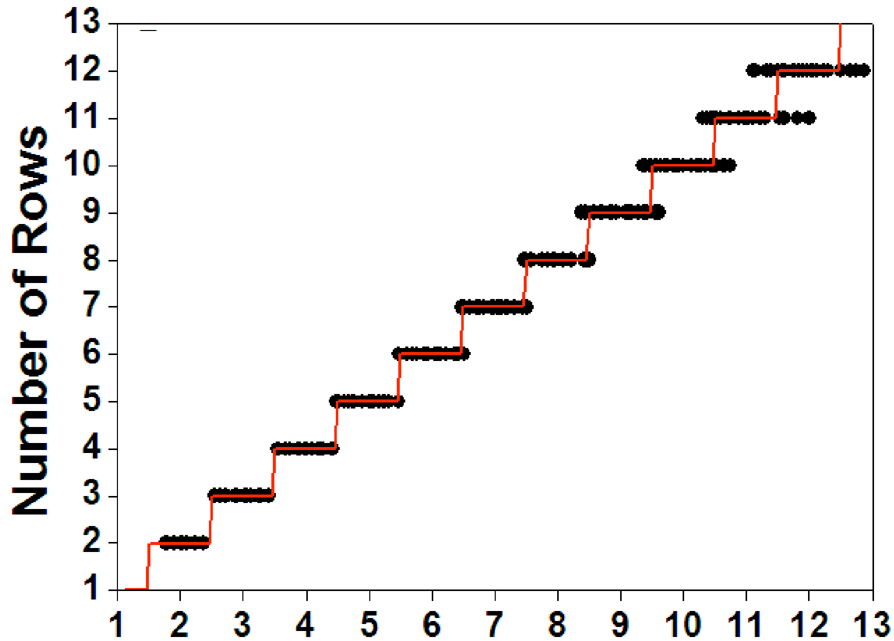


Of particular interest is to obtain features smaller than the lithography limit.

Ordering Block Copolymers using Patterned Substrates



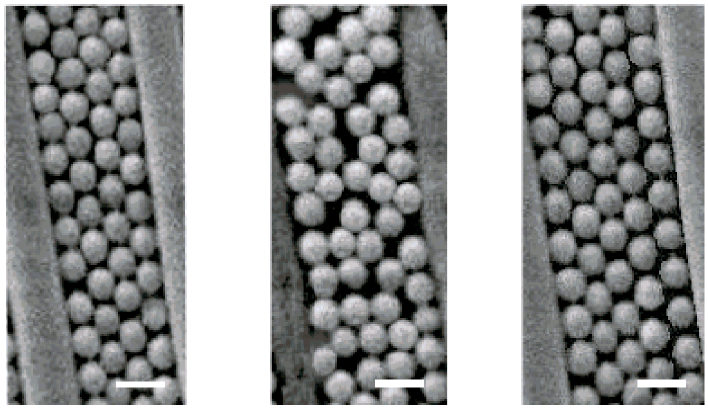
Quantized numbers of rows of spheres in the grooves



Groove width (in multiples of polymer period)

The row spacing adjusts if the groove width is incommensurate with the polymer period. The PFS spheres are smaller near the sidewalls and larger in the center of the grooves.

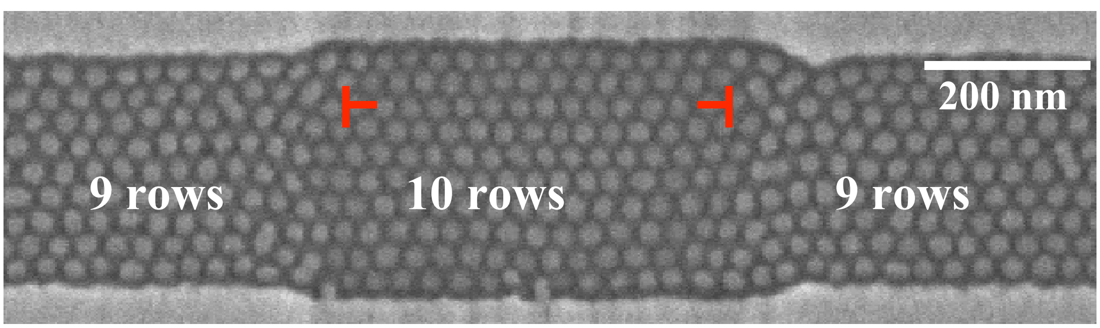
➢ The behavior is very different from the ordering of colloidal spheres in substrate topography. The block copolymer adjusts to be commensurate with the substrate for all groove widths. In colloidal sphere packing, ordering only occurs for certain groove widths.

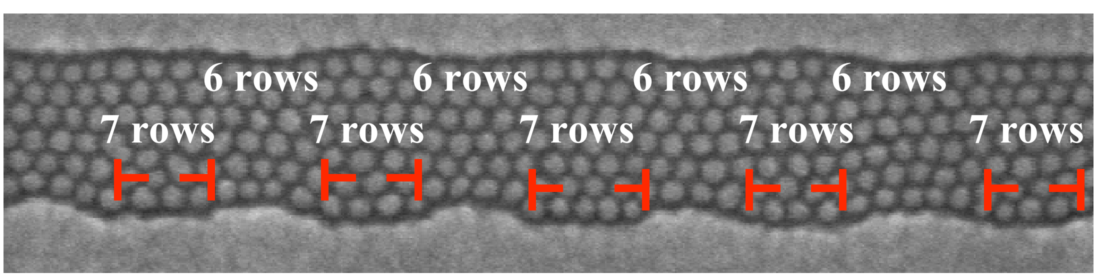


2.22 μm 2.51 μm 2.72 μm

E. Kumacheva, R. K. Golding, M. Allard, E. H. Sargent, *Adv. Mater.* 14, 221 (2002)

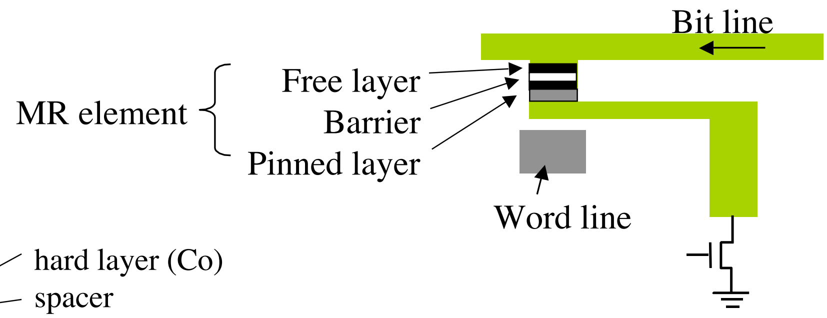
Introducing 'Defects' in block copolymer arrays

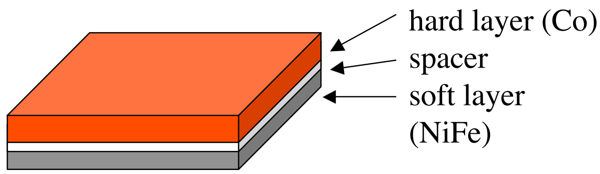


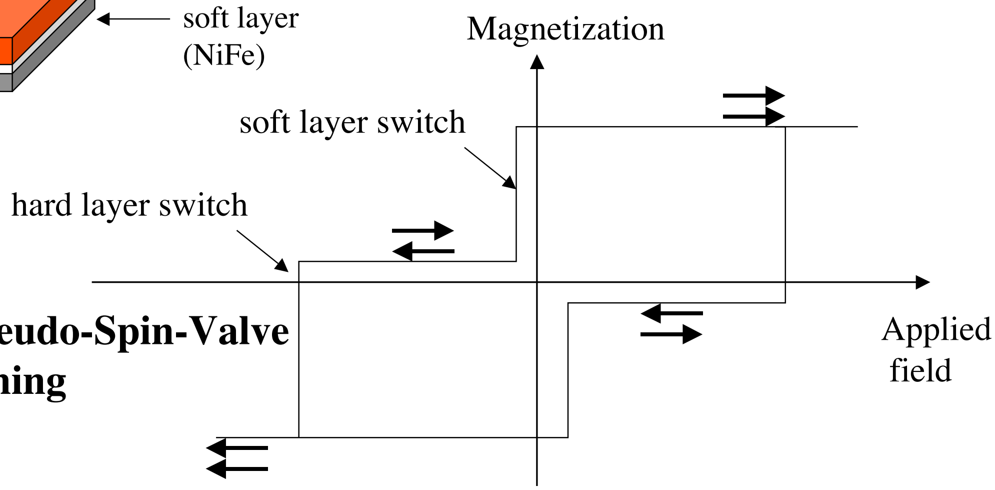


Dislocations can be introduced by varying the template width.
Number of dislocations can be tuned by the template.

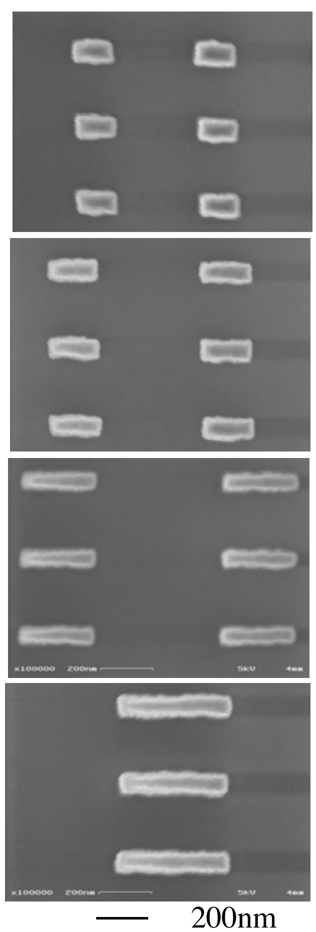
Behavior of multilayer elements for MRAM applications

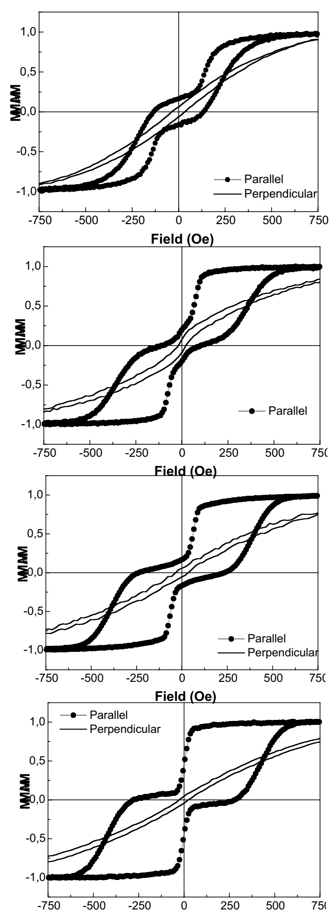






Idealized Pseudo-Spin-Valve (PSV) switching



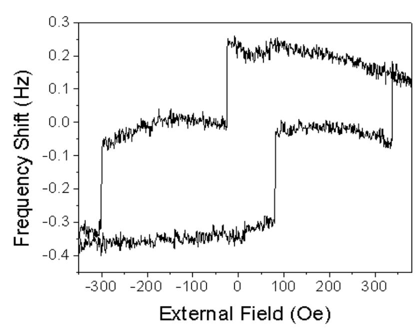


Reversal in PSV Elements

NiFe (6 nm)/ Cu (3 nm)/ Co (4 nm)/ Cu (4 nm)

NiFe switching fields are determined by competition between exchange (which keeps the Co and NiFe parallel) and magnetostatic coupling (antiparallel).

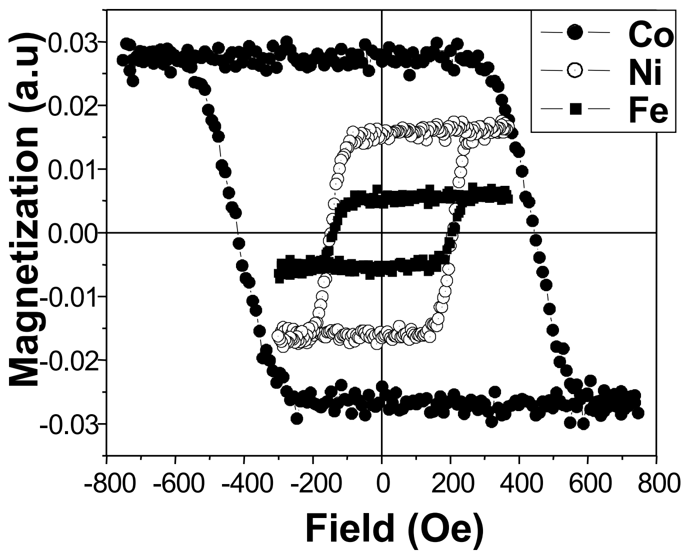
Single elements behave ideally.



Reversal of Nanoscale Pseudo-Spin-Valve Elements

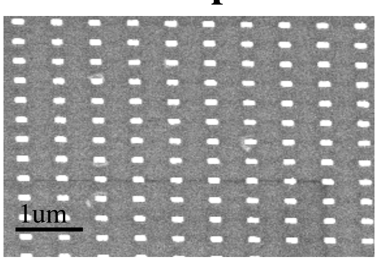
Magnetic circular dichroism gives chemically-specific hysteresis loops
~ 10^9 nanomagnets, 70 x 550 nm^2

C. Sánchez-Hanke, C-C. Kao, BNL

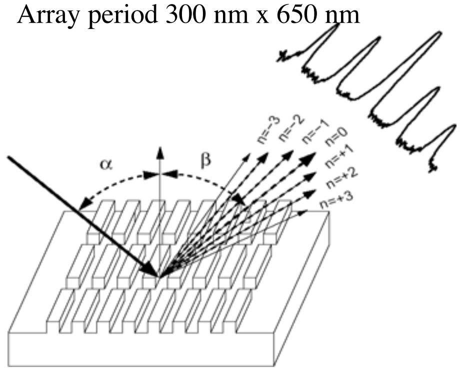


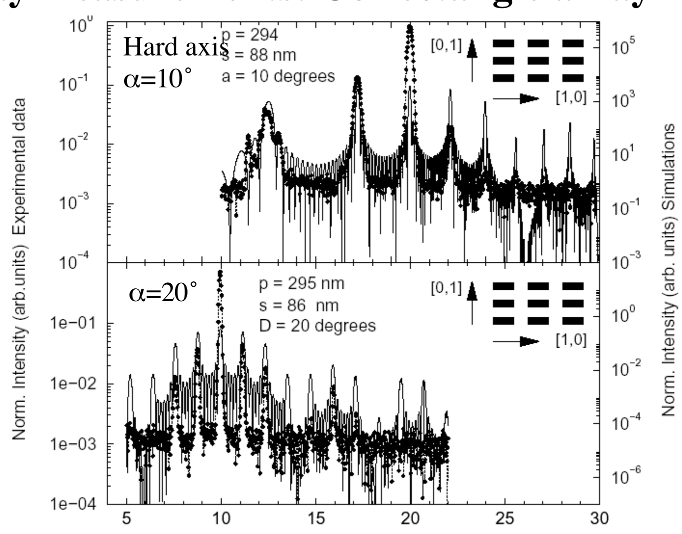
Similar to what is seen from minor loops measured by magnetometry and MFM, the offset of the NiFe loops represents the interaction field exerted by the Co layers (60 Oe)

Another example of soft x-ray measurements: Co rectangle array

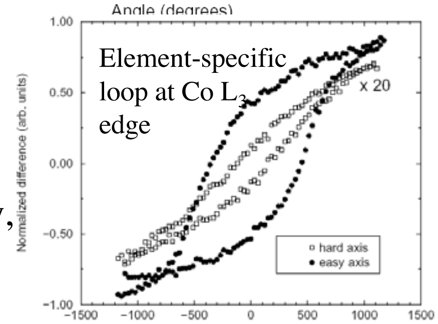


Co 10 nm x 90 nm x 200 nm
Array period 300 nm x 650 nm





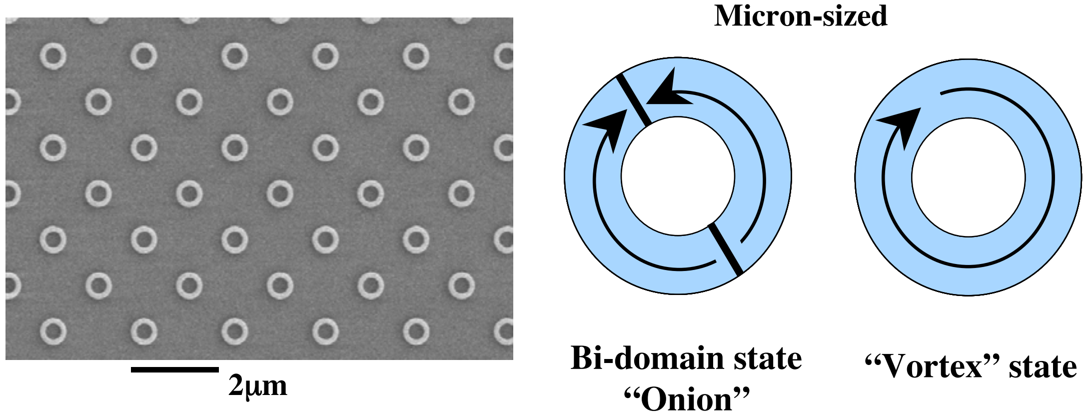
Diffraction of soft x-rays from rectangle array gives information about the periodicity, magnetic structure and correlations between neighbors.



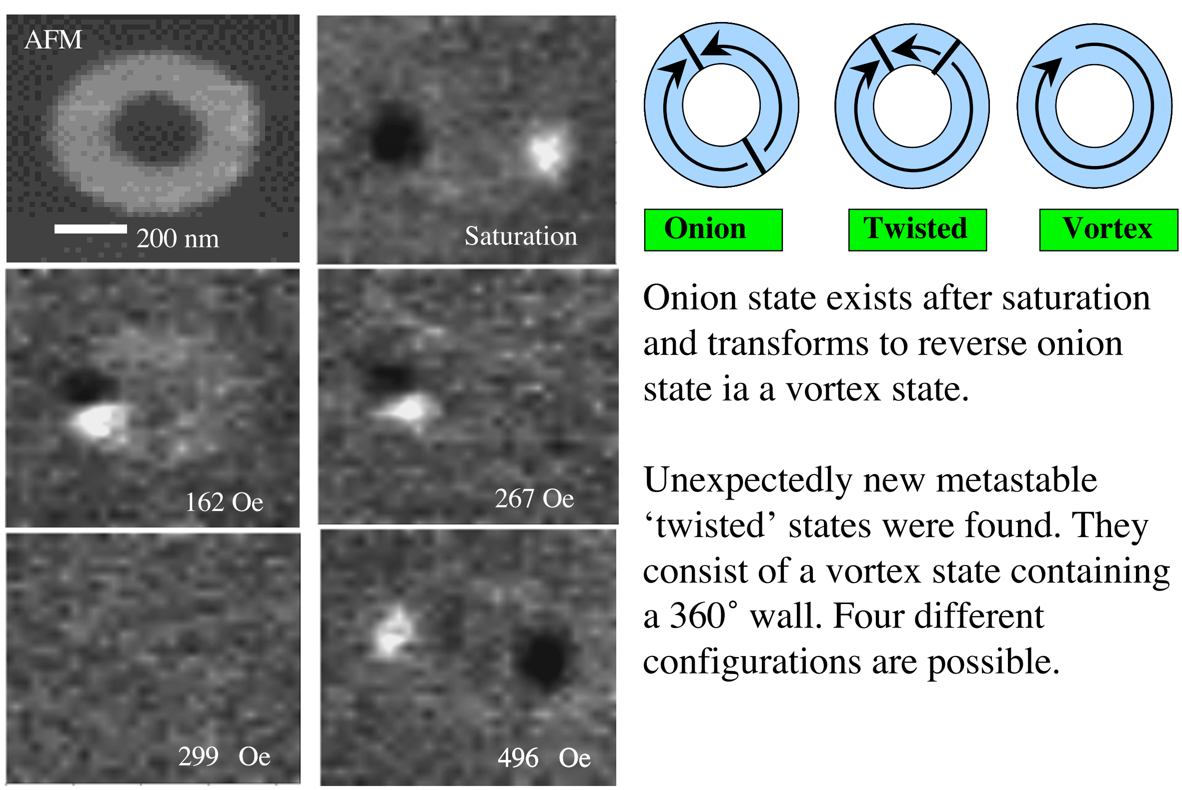
Is there another choice for the shape of the magnetic elements in MRAMs?

Ring-shaped elements can also be used in magnetoelectronic applications: the data can be stored as clockwise or counter-clockwise magnetic states ('vortices').

Rings can also be magnetised in an 'onion' state.



Remanent states of submicron Co rings

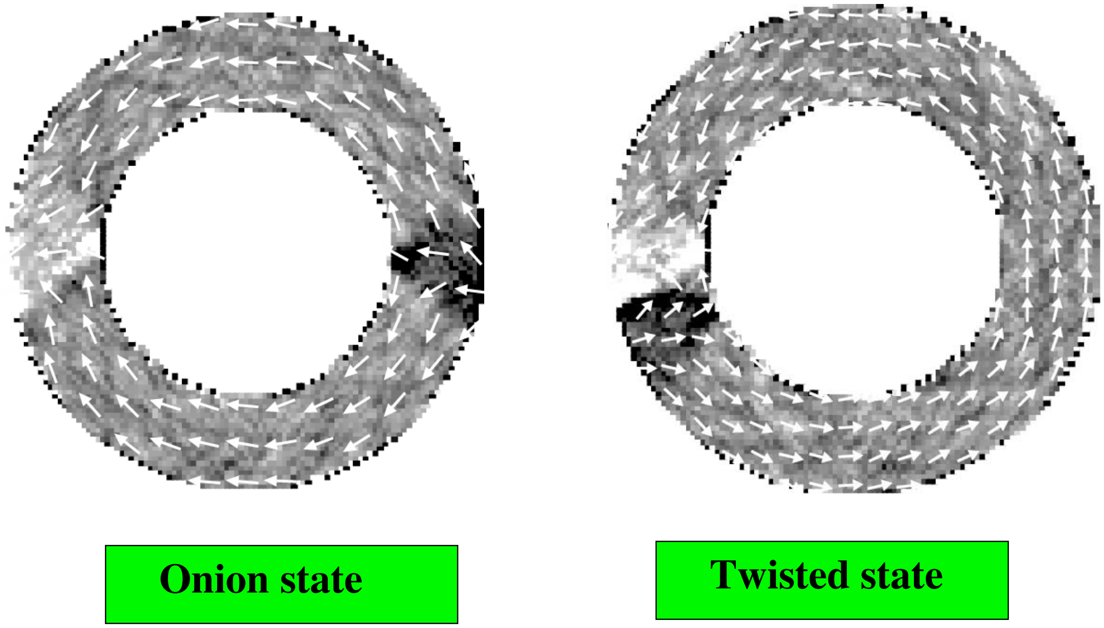


Onion state exists after saturation and transforms to reverse onion state ia a vortex state.

Unexpectedly new metastable 'twisted' states were found. They consist of a vortex state containing a 360˚ wall. Four different configurations are possible.

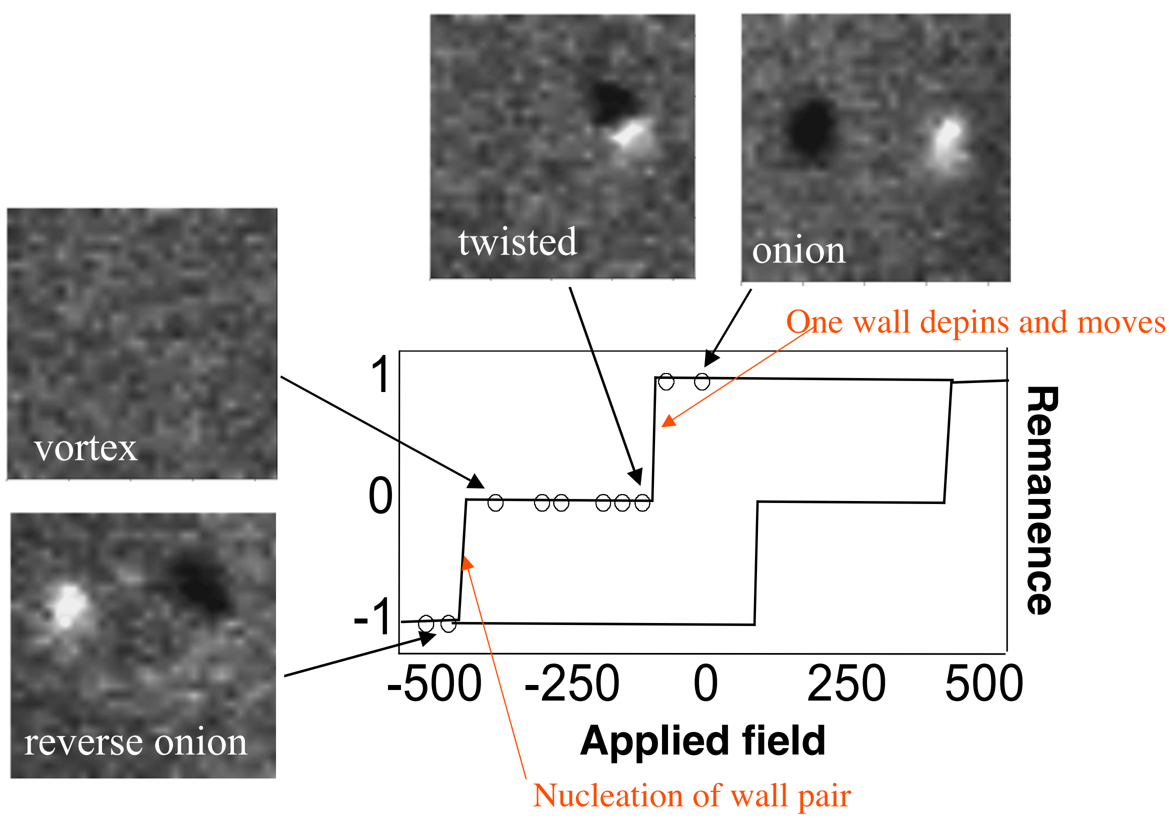
What is the nature of the 'twisted state'?

Micromagnetic model of remanent states of 320 nm diameter Co ring

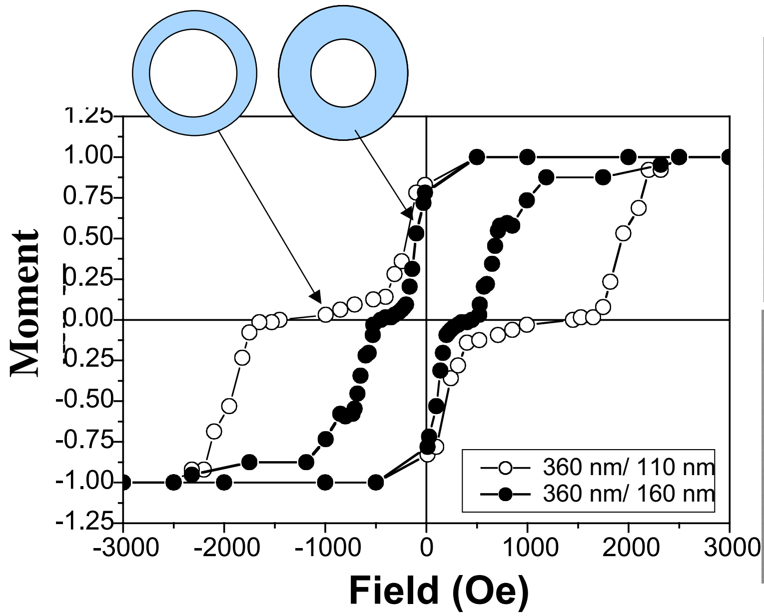


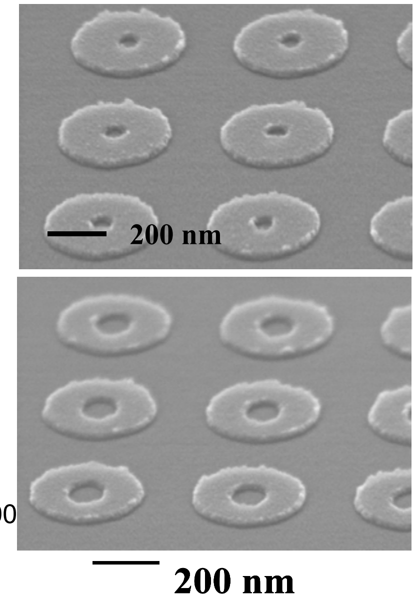
The magnetization rotates through 360˚ about an axis perpendicular to the film plane in small diameter, narrow rings.

Remanent loop for a 520 nm diameter Co ring



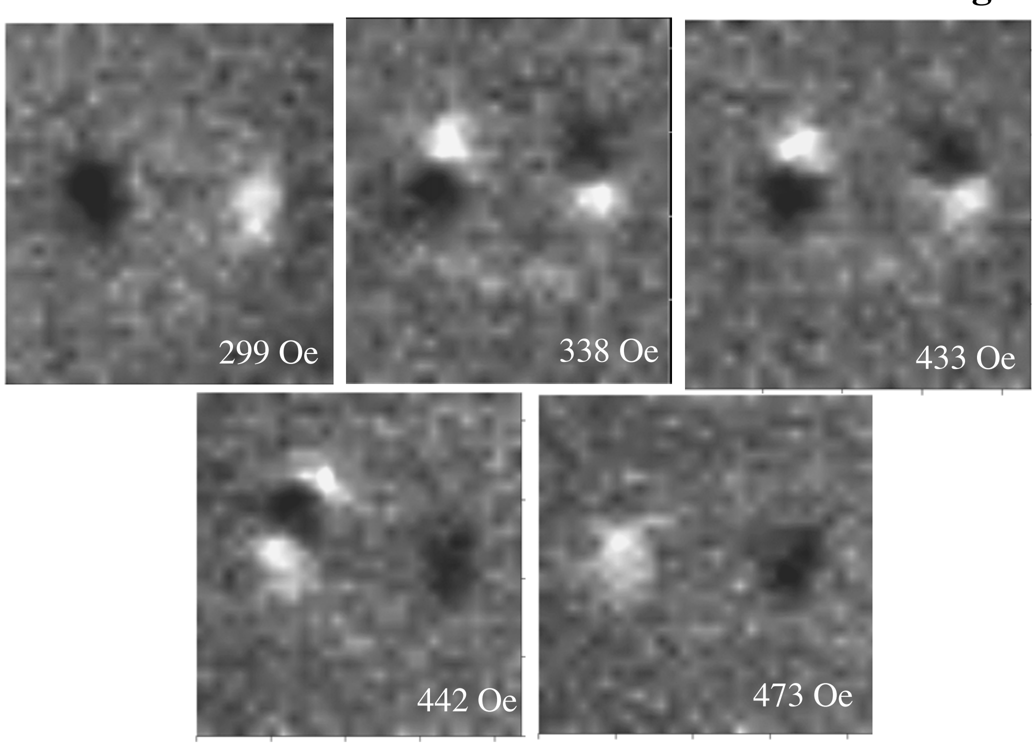
Hysteresis loops of submicron Co rings





The switching field for each transition increases as the ring width is decreased.

Can other remanent states exist in submicron Co rings ?



Complex configurations such as double twisted states with two 360˚ walls have been observed.

Conclusions

Patterned recording media, in which each nanostructure stores one bit, may be the next generation of hard disk media. Block copolymer lithography can create high density (> 250 Gparticles/ in^2), low cost dot arrays with adjustable spacing (29~60 nm) and diameter (18~35 nm). Long-range ordering can be induced through topographic templates, allowing controlled 'defects' (aperiodic structures) to be introduced. This 'templated self assembly' could be useful for many other nanotechnology applications.

Magnetic Random Access Memory is the next generation of non-volatile solid-state memory. Ring-shaped elements may provide an alternative geometry, with perhaps an increase in the possible number of bits stored per ring.

Synchrotron measurements are needed to provide valuable data on reversal mechanisms of individual layers, interface structure and magnetism, and effects of interactions within small complex structures.